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The influence of traveling magnetic field inductor asymmetric power supply on the liquid metal flow

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Abstract. In modern times, exposure to a liquid metal by a travelling magnetic field is widely applied. There are laboratory studies on the processes of stirring and crystallization under the action of a traveling magnetic field. However, in the majority of studies it is assumed that the inductor power supply of the linear induction machine is carried out by a symmetrical three-phase system of currents with an equal phase shift, which, in some cases, is not quite correct. To approximate the model to real operating conditions, a numerical simulation of the magnetic field and the flow of liquid metal was carried out when supplied from a power source of symmetric three-phase voltage. The distortion of magnetic field, which, in turn, causes a nonuniform distribution of forces and the flow of a liquid metal, is shown. Evaluation of asymmetrical effect on the liquid metal flow was carried out by means of finite element method. That effect is caused by different coefficients of mutual coils induction of the linear induction machine, which is confirmed by experimental data.

1. Introduction

Application of magnetic fields in a modern metallurgy play an important role. Control of stirring and transport of melt can be contactless provide by magnetic field influence. That method many decades approves his advantages but from another hand it demands additional costs for research. Numerical simulation is a good tool for investigators due to opacity, high temperature and aggressiveness of liquid metals. Many developers use the simplifications in an electromagnetic part of the numerical models. It can be helpful for both model developing time and computation power demands. But sometimes that simplification includes a special aspect and can influence on a numerical results, especially in the case of non-ideal inductor [1].

Alternating magnetic field influence can be divided on three cases: one phase coil, rotating and travelling magnetic field. In the last case, the travelling magnetic field (TMF) is generated by inductor or stator of linear induction machine. That device has a several differences with compare to rotating machines. TMF inductors have a longitudinal and transverse end effect. Besides of forces distribution that leads to unsymmetry resistance in coils and hence to differences in electrical current values. Some theoretical works consist of ideal TMF wave and do not take into account a real inductor [2]. But usually authors set the equal current density value in all three phases and shift between them 120° [3, 4]. For some types of windings it can be different in reality [5, 6].

In present work we suggest to compare ideal (symmetrical) and real (asymmetrical) coil current cases for TMF stirring application. The study is based on the installation of a travelling



magnetic field stirring shown in Fig. 1 presented in [7–9].

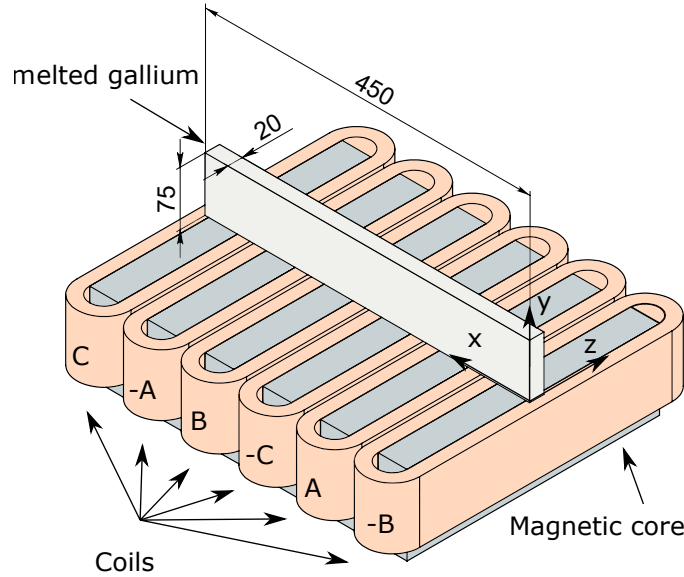


Figure 1. TMF stirring installation appearance.

2. Methods

2.1. Numerical EM and CFD model

The 3D numerical calculations were carried out by the finite element method using the Comsol Multiphysics software. At the first stage for electromagnetic calculations we used the Maxwell equations, which were formulated in terms of the magnetic vector potential in frequency domain.

$$\nabla(\nabla \times \mathbf{A}) = \begin{cases} j\mu\omega\gamma & \text{for non-conducting domains} \\ j\mu\omega\gamma + \mathbf{J}_{ext} & \text{for conducting domains} \end{cases} \quad (1)$$

$$\mathbf{E} = -j\mu\omega\mathbf{A} \quad (2)$$

where \mathbf{A} is the magnetic vector potential, μ is the magnetic permeability, ω is the angular frequency, γ is the electrical conductivity, \mathbf{J}_{ext} is the external current density, \mathbf{E} is the electric field.

As was mentioned above the study divided in two cases. The first case is a usual uniform distribution of current density in the inductor coils. It means that external current is specified directly by the current density.

For the second case external current is specified indirectly by calculated voltage taking into account equivalent circuit and cascade coil connection. Calculation is provided according to Kirchhoffs circuit laws for equivalent circuit (Fig. 3).

$$\mathbf{E}_{coil} = \int \mathbf{E} dL \quad (3)$$

$$R_{coil} = \int \frac{N\mathbf{L}}{\sigma S\Sigma} d\Sigma \quad (4)$$

where R_{coil} , N , L , σ , S and Σ are the total resistance of the coil, the number of turns, the coil length, the wire bulk conductivity, the wire cross-section area and the total cross-sectional area of the coil domain respectively. Integration was provided over coil conductors length.

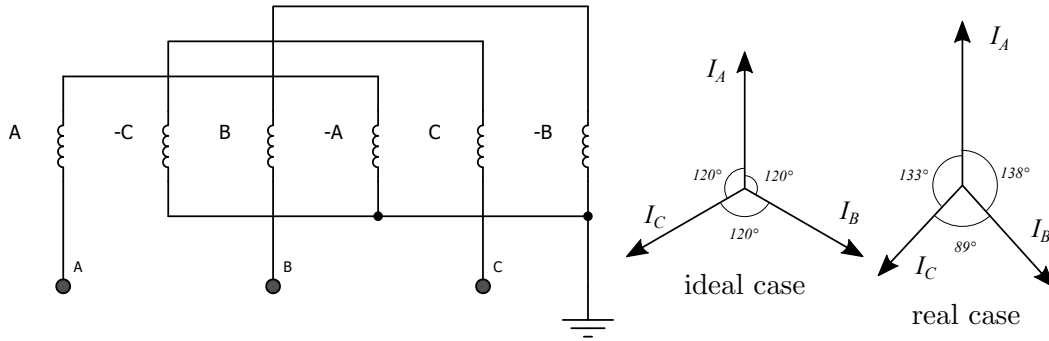


Figure 2. Windings connection scheme and coil current vectors

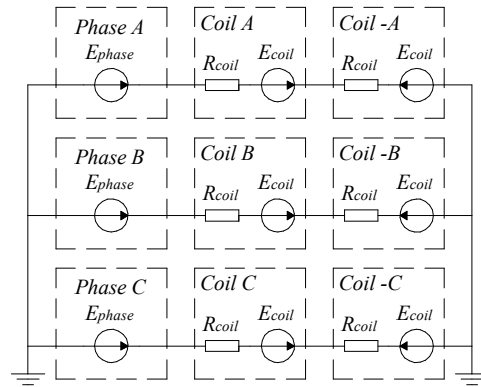


Figure 3. Equivalent circuit for asymmetry calculation

The calculations of the magnetic field, induced current and Lorenz force distribution were made with the use of the Comsol Magnetic Fields interface. Under the assumption of low magnetic Reynolds number ($Re_m = 0.065$), the induced current density was calculated by noninductive formulation [3, 10, 11].

Further the Lorenz force density are used in CFD calculations. For evaluation of turbulent flow dynamics the Large Eddy Simulation (LES) turbulence model was chosen. That approach allows to resolve the large unsteady eddies by the mesh, whereas the effect of smaller eddies at the mesh element scale or below are approximated. That method is demands a more computing power but from another hand can give more precision result of recirculated flow.

2.2. Experimental verification

We suggest to validate the numerical results by comparison with experimental data. The validation is carried out by magnetic flux density in the air gap between inductor and liquid metal. Magnetic flux was measured in the y and x directions. The second parameter is the time-averaged velocity profile measured by Ultrasound Doppler Velocimetry. The sensor was placed on the wall of the cell at height 29.5 mm from the vessel bottom. The detail experimental setup and measured systems description can be found in [9, 12].

3. Results

At the first step the magnetic flux density is obtained. Cut surface in a middle of liquid metal domain is shown in Fig. 4. The two cases of symmetrical and asymmetrical inductor power supply are compared. As was expected the first case gives the uniform distribution with a local peaks close ot magnetic core tooth. For the second "asymmetrical" case differences of

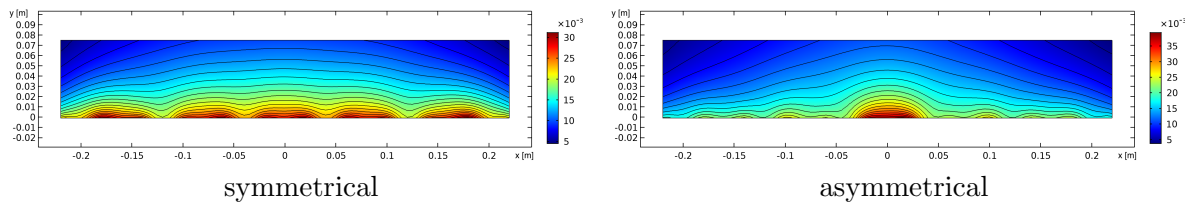


Figure 4. Magnetic flux density in the liquid metal.

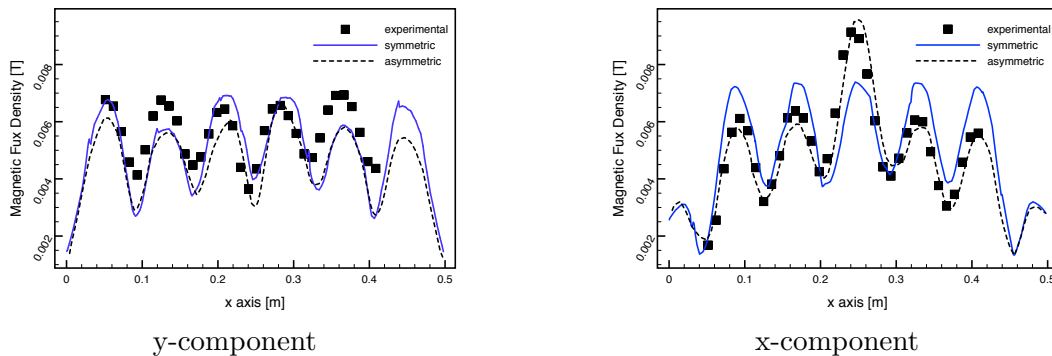


Figure 5. Magnetic flux density in the air gap.

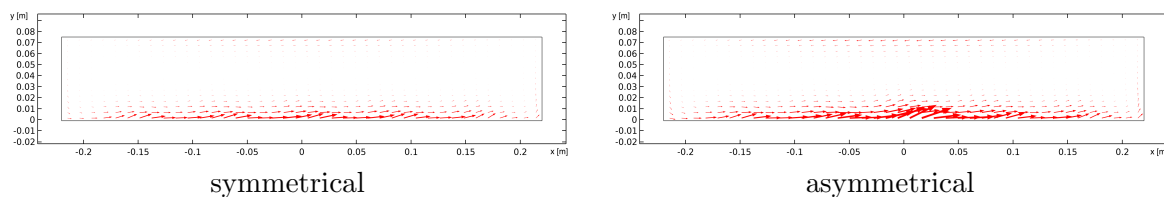


Figure 6. Lorenz force distribution in a liquid metal volume.

current magnitudes and phase shifts between them lead to the uniform distribution of magnetic flux density. In a middle of the cell the magnetic field peak is appear. That phenomena can be explained by decreasing of phase shift angle between currents I_B and I_{-A} from 120° to 89° (see Fig. 2), which is placed in one magnetic core slot.

The comparison of magnetic flux result is shown in Fig. 5. The y-component reaches maximum above magnetic core tooth and the x-component of magnetic flux has the maximum value above slots where fluxes are connected. As was expected from Fig. 4 we can observe the peak of magnetic flux above the middle slot. Asymmetrical approach has a good agreement with the experimental data. On the other hand symmetrical approach gives the uniform distribution of magnetic flux density.

The product of magnetic flux density and current density is the Lorenz force. Fig. 6 represents the magnitude and direction of electromagnetic forces in melt. The forces are directed along x-axis. Consequently from the magnetic flux result Lorenz forces also has a difference between two cases. In the symmetrical case forces are distributed uniformly mostly in the bottom area of the melt. On the other hand asymmetrical case gave also peak on the middle of the cell and, moreover, x-component magnetic field generated the deviation of forces vectors from x to y component.

The next step of calculation is the fluid dynamic computation under the Lorenz forces (Fig. 7). Due to the fact that forces are applied mostly to the bottom region of the fluid layer and directed along x-axis the primary vortexes are generated at the bottom surface. It should be underlined

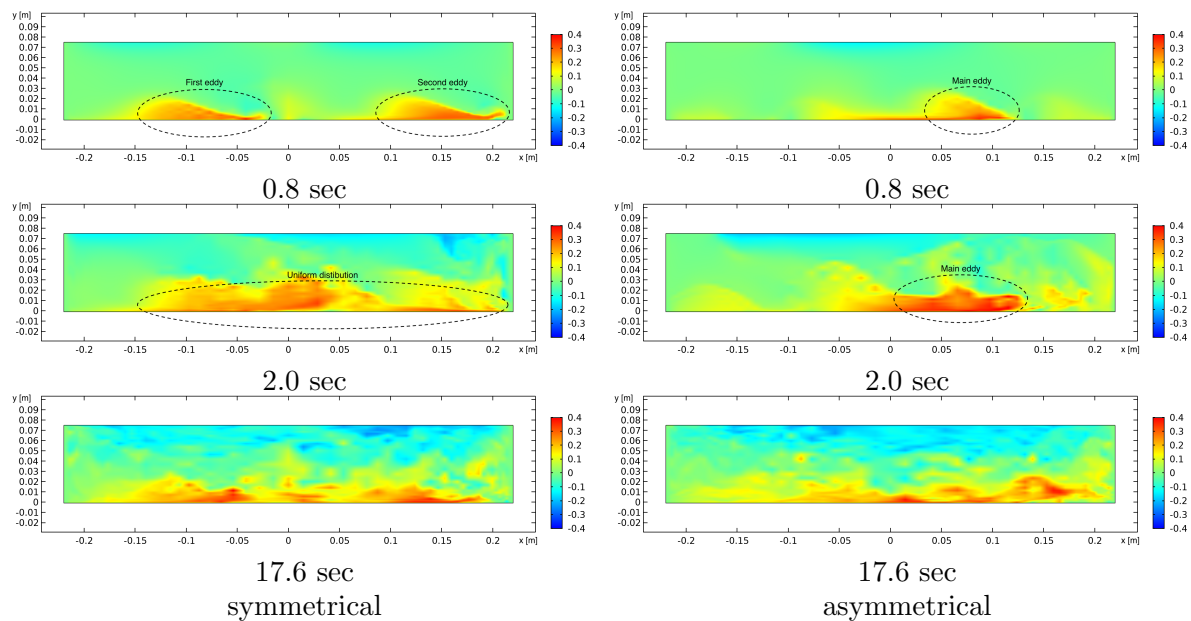


Figure 7. X-component of velocity dynamics under symmetrical and unsymmetrical TMF cases.

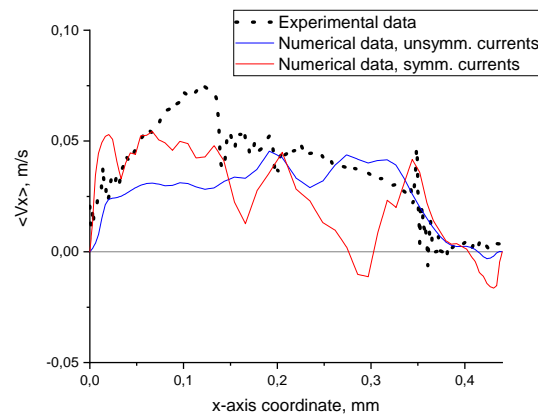


Figure 8. Comparison of mean velocity profile with UDV experimental data.

that in two cases we have the different flow pattern. In the symmetrical case the two vortices are appear due to uniform forces distribution. In contrast, the asymmetrical case leads to one main vortex in the middle of the cell. That phenomena is explained by the magnetic field peak mentioned above. Further the flow patterns stay different. In the asymmetrical case main vortex starts generates in the middle zone. Under that influence the liquid starting under clockwise rotation. As it was expected the flow is highly unstable and one can conclude that LES approach can be useful for EM stirring calculation.

Comparison of numerical and experimental obtained x-component of time-averaged velocity profiles presented in Fig. 8. The both cases have a good agreement, but don't show near the wall eddy. On the rest part of the curve the asymmetrical case has a better agreement with experimental data.

4. Conclusions

In the presented work, a numerical simulation of a linear induction machine with a liquid metal secondary element by finite element method was carried out. Two cases of current excitation in TMF inductors coils are considered. For taking into account coil current asymmetry the equivalent circuit technique was suggested.

Considering asymmetry of TMF inductor coil currents it was shown that the asymmetry has a certain influence on simulation result. On the one hand it affects on the magnetic flux distribution, which allows to achieve well agreement with experimental data (Fig. 5). On the other hand this results in non-uniform Lorenz forces distribution and influences on the fluid flow dynamics. The magnetic flux density increase at the middle part of the inductor generates one large-scale vortex instead of uniform flow velocity distribution. Comparison of the proposed method with UDV measurements demonstrates more accurate determination of the velocity characteristics.

Considering the results obtained in the previous studies of TMF stirrers [4, 7, 13, 14] it can be mentioned that the proposed approach of currents determination allows one to increase the accuracy of model. Therefore the usage of the equivalent circuit method is justified in the case of pronounced asymmetry. So it can be concluded that the goal of the work has been achieved. The chosen method provides good comparison with the experimental data and can be widely used in the field of applied magnetohydrodynamics.

The next step in the frame of the global project is model of TMF low-frequency modulations influence on the rising MHD flows and stirring efficiency. It allows to predict the effect of the TMF and forced convection action during solidification process, the solidification rate and front shape. Concerning the developed method, it could be important to estimate the effect of other phase shifts of the LIM power supply caused by asymmetric compensation, as well as investigate other constructions of LIM for subject of asymmetry.

Acknowledgments

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